Unidirectional shear horizontal wave generation by periodic permanent magnets electromagnetic acoustic transducer with dual linear-coil array

Alan C. Kubrusly, Lei Kang and Steve Dixon

***Abstract*— Shear horizontal (SH) waves are commonly generated by periodic permanent magnet (PPM) electromagnetic acoustic transducers (EMATs) in metallic media. Conventional PPM EMATs generate ultrasonic waves which simultaneously propagate both forwards and backwards. This is usually an undesirable characteristic since the backward wave can be eventually reflected reaching the receiver transducer where it can mix with the signal of interest. This limitation has been recently overcome by our new unidirectional SH-EMAT with two side-shifted PPM arrays and racetracks coils. This design relied on the wavefront diffraction to produce constructive and destructive interferences, but presented unwanted backward side-lobes. Here we present a different design which uses a conventional PPM array and a dual linear-coil array. The concept was numerically simulated and the unidirectional EMAT was experimentally evaluated in an aluminum plate generating the SH0 guided wave mode nominally in a single direction. The ratio of the generated waves at the enhanced to the weakened side is above 20 dB. Since the wavefronts from the two sources are perfectly aligned, no obvious backward side-lobes are present in the acoustic field, which can significantly reduce the probability of false alarm of an EMAT detection system.**

***Index Terms*— Electromagnetic acoustic transducers; unidirectional generation; shear horizontal waves; guided waves**

I. Introduction

SHEAR horizontal (SH) are widely used for defect inspection in plates and pipes [1, 2, 3, 4, 5, 6] due to its advantages, such as simple dispersion relationship, the possibility of readily operating with a single non-dispersive mode and no energy loss to non-viscous liquid loading. SH waves can be generated either by a periodic permanent magnet (PPM) electromagnet acoustic transducers (EMATs), shear-polarized piezoelectric strips [7, 8], or by magnetostrictive patch transducers [9]. The former has the remarkable advantage of not requiring contact with the sample, whereas the others have to be properly bonded to the surface of the sample.

A PPM EMAT typically consists of a periodic permanent magnet array and a racetrack coil [10, 11]. Ultrasonic waves are generated through the Lorentz principle in which forces are induced in the sample given by the cross product between the bias magnetic field, produced by the magnet array above the coil, and the induced eddy current in the sample [12]. Due to the arrangement of the magnets and racetrack coil, the induced forces generated by a PPM EMAT are parallel to the surface of the sample and perpendicular to the propagation direction, generating SH waves. Conventional PPM EMATs generate waves that propagate both forwards and backwards. This can complicate the interpretation of the received signal, since the backward propagated wave can be eventually reflected or directly arrives at the receiver due to a closed-loop propagation path, like circumferential inspection of pipes [1], being thus mixed with the signal of interest. Therefore, unidirectional generation provides a more reliable inspection.

Efficient unidirectional generation of ultrasonic waves is possible if two ultrasonic sources are separated by a quarter-wavelength, $\lambda/4$, and excited by 90° delayed pulses, which was previously used for generating other modes of ultrasonic waves with EMATs [13, 14]. Conventional PPM EMATs do not support this principle of unidirectional generation, since the position and direction of forces are dictated by the magnets of the PPM array, which share the same racetrack coil underneath the magnet array. This constraint was discussed in detail in our previous letter [15], where we proposed a solution with two side-shifted interlaced racetrack coils and PPM arrays, which is shown in Fig.1. According to the adopted Cartesian axes, the induced eddy currents in the sample are in the x-direction and the magnet field of each magnet in the y-direction, with alternate polarities, thus generating Lorentz forces in the z-direction and consequently SH waves that propagate in the x-direction. Since the PPM arrays are longitudinally shifted by $\lambda/4$, unidirectional propagation is obtained when the second one is excited with 90° delay. Its operating principled relies, however, on the wavefront diffraction from both sources since induced forces from each PPM array are shifted in the z-direction, as schematically shown in Fig.1. Despite generating virtually no backward propagating wave on the x-axis, this

This work was supported in part the Brazilian National Council for Scientific and Technological Development, CNPq, and by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001.

A. C. Kubrusly is with Centre for Telecommunication Studies, Pontifical Catholic University of Rio de Janeiro, Rio de Janeiro, 22451-900, Brazil (e-mail: alan@cpti.cetuc.puc-rio.br).

L. Kang is with the School of Energy and Electronic Engineering, University of Portsmouth, Portsmouth, PO1 3DJ, UK (e-mail: lei.kang@port.ac.uk).

S. Dixon is with the Department of Physics, University of Warwick, Coventry, CV4 7AL, UK (e-mail: S.M.Dixon@warwick.ac.uk).

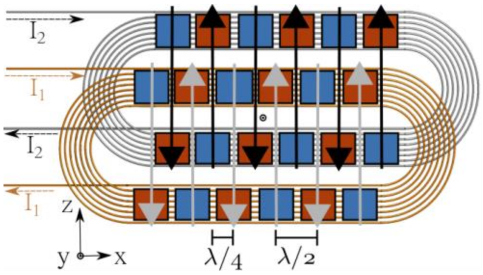

Fig. 1. Unidirectional side-shifted PPM EMAT with two racetrack coils presented in [15]. Red and blue blocks represent the magnets' poles. The dashed lines represent the current injected into each racetrack coil. Generated Lorentz forces from each array are schematically represented by vertical grey and black arrows.

arrangement produces non-negligible backward side-lobes from an interference mechanism, which can yet introduce some reflected signal from the weakened-side semi-plane.

Here we propose an alternative design of a unidirectional SH EMAT with one conventional PPM array and a different coil geometry, which also effectively generates SH waves in a single direction and, unlike the previous design shown in Fig.1, does not present backward side-lobes.

II. Design of PPM EMAT with dual linear-coil array

In order to introduce two independent ultrasonic sources that are capable of generating SH waves, i.e., alternate forces along the z-direction and propagation along the x-direction, we use the conventional PPM array layout, but without the usual racetrack coil design. Instead, a dual linear-coil array is used, as shown in Fig. 2(a). Each element of the linear-coil array consists of a conductive wire wrapped around a single rectangular magnet, which individually operates as a linear-coil EMAT [16, 17]. Note that, similar to Fig.1, the current induced in the skin-depth of the sample still lies in the x-direction, but since there is no racetrack coil underneath the magnets, one is able to associate adjacent magnets with different currents without the need for shifting half of magnets sideways. Also, since this new EMAT has the classical PPM arrangement of alternating polarities of magnets, the EMAT is robust, because attraction forces between adjacent magnets act to form a stable array as a whole. Special attention has to be paid to the winding of each element of the coil array which has to be alternated between clockwise and counter-clockwise due to the alternate polarity of magnets, as shown in Fig. 2(a). This way, the dual linear-coil array generates the force pattern shown by the vertical arrows. Consecutive forces originated from the same coil array have alternate polarity and thus define a distance of half-wavelength ($\lambda/2$). Consequently, adjacent forces from different coil arrays are separated by a quarter-wavelength ($\lambda/4$). Unidirectional generation is then obtained when exciting the second coil array delayed by 90º.

The proposed design was fabricated with the dimensions shown in Fig. 2(b). The length and the width of each magnet are 4 mm and 20 mm, respectively, and the gap between magnets is 2.2 mm, creating a nominal wavelength of about $\lambda = 25$ mm. The magnet and linear-coil arrays assembly was mounted in a 3D-printer former, to impose better alignment between adjacent magnet-coil pairs.

III. Results and discussion

Both finite element simulation and experimental evaluation were performed to assess the performance of the unidirectional PPM EMAT with dual linear-coil array generating the non-dispersive SH0 guided wave mode [18] in a 1.5 mm aluminum plate.

For the three-dimension numerical simulation, the plate was modelled with an SH0 or transverse wave speed $c_T = 3111\, m/s$ and forces were applied along the z-direction at predefined regions on the surface of the model that correspond to the areas under each magnet and coil element, where the Lorentz forces are generated, following the design shown in Fig. 2(a) with the dimensions of the fabricated EMAT. This approach allows one to generate SH guided waves without including the EMAT coupling mechanism in the numerical simulation, as validated previously elsewhere [4, 5, 10, 15]. The direction of each force along the z-axis follows the vertical arrows in Fig. 2(a), obeying thus the Lorentz force pattern produced by each linear-coil array. Forces were modulated by an 8-cycle, sinusoidal tone-burst at 124 kHz and the ones corresponding to the second array are delayed by 90º, relative to the first, in order to simulate the delayed driving current applied to the second coil array. Fig. 3 shows a snapshot of the generated wavefield when the center of the generation location is at the origin. One can see that it generates an SH wave travelling to the right with a negligibly small amplitude signal

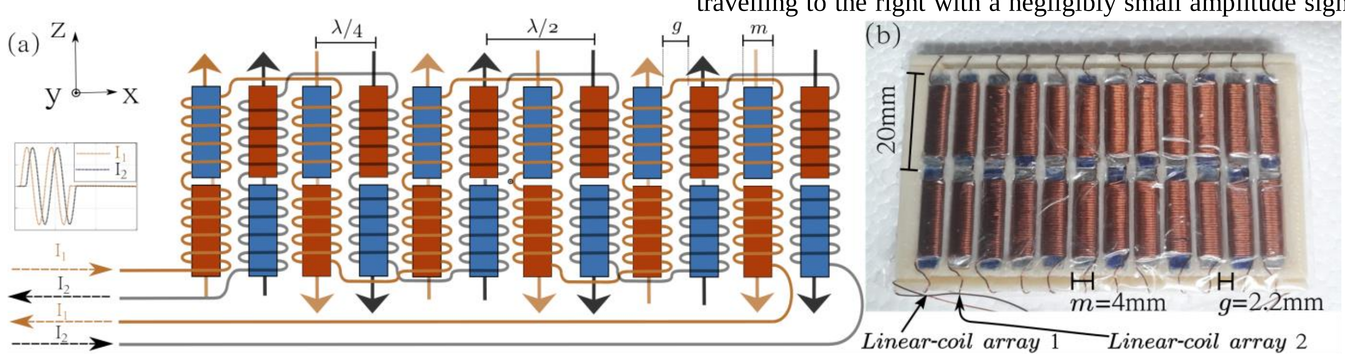

Fig. 2. Design of unidirectional PPM EMAT with dual linear-coil array (a). Red and blue blocks represent the magnets' poles and the linear-coil arrays are represented by copper-color and grey wires. Magnets' length is m and the gap between magnets is g. Each element of the linear-coil arrays is wound around an individual magnet in the correct sense so induced Lorentz at the same column have the same direction. Forces generated by the first array are represented by vertical copper-color arrows, whereas the ones related to the second array with black vertical arrows. The dashed lines represent the currents I_1 and I_2 injected into coil arrays 1 and 2, respectively. I_2 is 90º delayed respect to I_1, as represented by the dotted-line signals in the left inner plot. Photograph of fabricated unidirectional dual linear-coil array SH EMAT with dimensions (b).

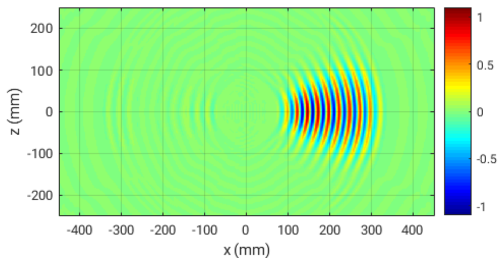

Fig. 3 Snapshot of normalized wavefield at 100 μs at the top surface of the plate.

travelling to the left.

To experimentally assess the proposed design, a two-channel signal generator synthesized two 8-cycles tone-bursts at 124 kHz, being the second one 90º phase-shifted, which were power amplified and then connected to each linear-coil array of the unidirectional transducer. A conventional 3 cycles 25 mm nominal wavelength PPM EMAT was used as a receiver. Fig 4 shows the experimental received signals, superposed with numerically simulated signals, in the x-axis at both sides of the transmitter. As can be seen, the wave that propagates to the right is much stronger than the one that propagates to the left, experimentally confirming the unidirectional generation of the proposed design. The directivity diagram of the unidirectional transducer was also measured, both numerically and experimentally, and is shown in Fig. 5.

The ratio of the peak-to-peak amplitude of the received waves at 0º and 180º was 12.0, higher than the reported in previous work, where the SH waves were generated by piezoelectric strips [8] and slightly lower than obtained with the side-shifted unidirectional SH-EMAT design [15]. It is worth noticing that, the present design does not appear to present any significant amplitude backward travelling side-lobes, as can be seen either in the left-hand semi-plane of Fig. 3 or from 90º to 270º in Fig. 5. The highest amplitude in this angular interval is found at 180º, which is 21.6 dB below the main forward lode. Backward side-lobes were a drawback of the unidirectional side-shifted PPM EMAT [15], which showed non-negligible ones, close to 150º and 210º, as high as about 8.2 dB below the main forward lobe.

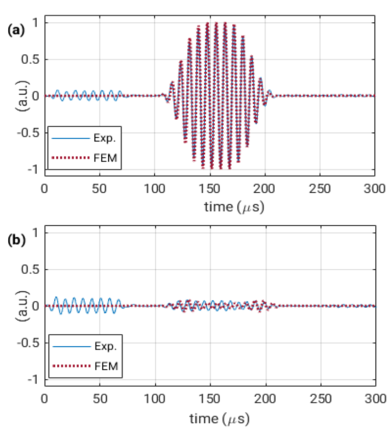

Fig. 4 Numerical, dotted line, and experimental, continuous line, received signals at x=+400 mm (a) and x= -400 mm (b). Amplitude is normalized per the maximum value of the received signal at the enhanced side. The signal for times around 50μs is the electrical interference from the driving current, and is therefore present only in experimentally measurements.

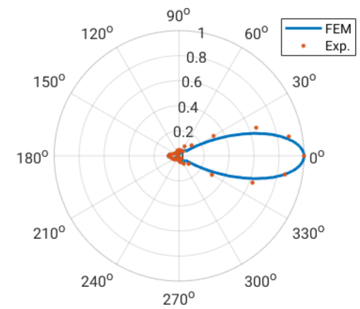

Fig. 5 Numerical, solid line, and experimental, red dots, directivity diagram for the unidirectional PPM EMAT with dual linear-coil array.

IV. CONCLUSION

Unidirectional wave generation can simplify the received ultrasonic signals, avoiding unwanted reflected waves or multi-turn waves in closed-loop paths, being thus of interest to the non-destructive evaluation field. Typical PPM EMATs do not support a second independent source of forces in order to generate unidirectional SH waves by means of longitudinally-shifted and delayed line sources method. Here we have proposed a new design of a unidirectional SH EMAT using the traditional PPM array but with a dual linear-coil array instead of the common racetrack coil. The fabrication process has to be enough precise to ensure that each element of the dual linear-coil array has the same number of turns, so the forces produced by all of them are nominally identical, as well as the proper winding sense is applied to each element.

Experiment and numerical simulation showed good agreement and confirmed that the proposed solution is effective in generating SH waves that propagate in a single direction with around 20 dB unidirectionality, similar to or higher than obtained elsewhere. The wavefronts produced by each independent source are aligned and thus provide ideally perfect interference, either constructive or destructive, generating unidirectional SH waves without backward side-lobes, which can significantly reduce the probability of false alarm of an EMAT detection system.

REFERENCES

[1] M. Clough, M. Fleming and S. Dixon, "Circumferential guided wave EMAT system for pipeline screening using shear horizontal ultrasound," *NDT and E International*, vol. 86, p. 20 – 27, 2017.

[2] N. Suresh and K. Balasubramaniam, "Quantifying the lowest remnant thickness using a novel broadband wavelength and frequency EMAT utilizing the cut-off property of guided waves," *NDT & E International*, vol. 116, p. 102313, 2020.

[3] O. Trushkevych, M. Tabatabaeipour, S. Dixon, M. Potter, G. Dobie, C. MacLeod and R. Edward, "Miniaturised SH EMATs for fast robotic screening of wall thinning in steel plates," *IEEE Sensors Journal*, p. Early Access, 2020.

[4] A. C. Kubrusly, J. P. von der Weid and S. Dixon, "Experimental and numerical investigation of the interaction of the first four SH guided wave modes with symmetric and nonsymmetric discontinuities in plates," *NDT & E International,* vol. 108, p. 102175, 2019.

[5] A. C. Kubrusly, M. A. Freitas, J. P. von der Weid and S. Dixon, "Interaction of SH guided waves with wall thinning," *NDT & E International,* vol. 101, pp. 94-103, 2019.

[6] P. Khalili and F. Cegla, "Excitation of Single-Mode Shear-Horizontal Guided Waves and Evaluation of Their Sensitivity to Very Shallow Crack-Like Defects," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control,* p. Early Access, 2020.

[7] H. Miao, Q. Huan, F. Li and G. Kang, "A variable-frequency bidirectional shear horizontal (SH) wave transducer based on dual face-shear (d24) piezoelectric wafers,," *Ultrasonics,* vol. 89, pp. 13-21, 2018.

[8] M. Chen, Q. Huan and F. Li, "A unidirectional SH wave transducer based on phase-controlled antiparallel thickness-shear (d15) piezoelectric strips," *Theoretical and Applied Mechanics Letters,* vol. 10, no. 5, pp. 299-306, 2020,.

[9] Y. Kim and Y. E. Kwon, "Review of magnetostrictive patch transducers and applications in ultrasonic nondestructive testing of waveguide," *Ultrasonics,* vol. 62, pp. 3-19, 2015.

[10] P. A. Petcher, S. E. Burrows and S. Dixon, "Shear horizontal (SH) ultrasound wave propagation around smooth corners," *Ultrasonics,* vol. 54, no. 4, pp. 997-1004, 2014.

[11] S. Hill and S. Dixon, "Frequency dependent directivity of periodic permanent magnet electromagnetic acoustic transducers," *NDT and E International,* vol. 62, pp. 137--143, 2014.

[12] M. Hirao and H. Ogi, Electromagetic Acoustic Transducers: noncontacting ultrasonic measurements using EMATs, Tokio, Japan: Springer, 2017.

[13] S. Wang, R. Su, X. Chen, L. Kang and G. Zhai, "Numerical and experimental analyis of unidirectional meander-line coil electromagnetic acoustic transducer," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control,* vol. 60, no. 12, pp. 2657 - 2664, 2013.

[14] X. Chen, R. Su, H. Zhang and G. Zhai, "Influence of coil parameters on transduction performance of unidirectional EMATs for Rayleigh wave," in *Far East Forum on Nondestructive Evaluation/Testing: New Technology and Application*, Jinan, 2013.

[15] A. C. Kubrusly, L. Kang and S. Dixon, "Unidirectional shear horizontal wave generation with side-shifted periodic permanent magnets electromagnetic acoustic transducer," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control,* vol. Early Access, 2020.

[16] C. Thring, S. J. Hill, S. Dixon and R. Edwards, "The effect of EMAT coil geometry on the Rayleigh wave frequency behaviour,," *Ultrasonics,* vol. 99, p. 105945, 2019.

[17] M. Rosli, R. Edwards and Y. Fan, "In-plane and out-of-plane measurements of Rayleigh waves using EMATs for characterising surface cracks," *NDT & E International,* vol. 49, pp. 1-9, 2012.

[18] J. L. Rose, Ultrasonic Guided waves in solid media, Cambridge University Press, 2014.